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# The X-Shooter Lens Survey – II. Sample presentation and spatially-resolved kinematics

C. Spiniello,<sup>1★</sup> L. V. E. Koopmans,<sup>2</sup> S. C. Trager,<sup>2</sup> M. Barnabè,<sup>3,4</sup> T. Treu,<sup>5,6</sup>  
O. Czoske,<sup>7</sup> S. Vegetti<sup>1</sup> and A. Bolton<sup>8</sup>

<sup>1</sup>Max-Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, D-85740 Garching, Germany

<sup>2</sup>Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, the Netherlands

<sup>3</sup>Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark

<sup>4</sup>Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

<sup>5</sup>Department of Physics, University of California Santa Barbara, Santa Barbara, CA 93106, USA

<sup>6</sup>Department of Physics and Astronomy, University of California, Los Angeles, CA 90025-1547, USA

<sup>7</sup>Institut für Astrophysik, Universität Wien, Türkenschanzstraße 17, A-1180 Wien, Austria

<sup>8</sup>Department Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

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## ABSTRACT

We present the X-Shooter Lens Survey (XLENS) data. The main goal of XLENS is to disentangle the stellar and dark matter content of massive early-type galaxies (ETGs), through combined strong gravitational lensing, dynamics and spectroscopic stellar population studies. The sample consists of 11 lens galaxies covering the redshift range from 0.1 to 0.45 and having stellar velocity dispersions between 250 and 380 km s<sup>−1</sup>. All galaxies have multiband, high-quality *HST* imaging. We have obtained long-slit spectra of the lens galaxies with X-Shooter on the VLT. We are able to disentangle the dark and luminous mass components by combining lensing and extended kinematics data sets, and we are also able to precisely constrain stellar mass-to-light ratios and infer the value of the low-mass cut-off of the initial mass functions (IMF), by adding spectroscopic stellar population information. Our goal is to correlate these IMF parameters with ETG masses and investigate the relation between baryonic and non-baryonic matter during the mass assembly and structure formation processes. In this paper, we provide an overview of the survey, highlighting its scientific motivations, main goals and techniques. We present the current sample, briefly describing the data reduction and analysis process, and we present the first results on spatially-resolved kinematics.

**Key words:** gravitational lensing: strong – galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: kinematics and dynamics – galaxies: structure – dark matter.

## 1 INTRODUCTION

Massive early-type galaxies (ETGs;  $\sigma \geq 200$  km s<sup>−1</sup>) contain more than half of the stellar mass in the Universe (e.g. Bell et al. 2003). Their internal structure and dynamics as well as the relationship between baryonic luminous matter and dark matter therefore provide key quantitative tests of the  $\Lambda$ colddarkmatter(CDM) cosmological paradigm (Blumenthal et al. 1984) and are crucial to fully comprehend the processes involved in the hierarchical formation of galaxies (e.g. White & Rees 1978; Davis et al. 1985; Frenk et al. 1985).

In hierarchical structure formation models, massive galaxies are believed to be formed through mergers of lower mass galaxies (e.g. Blumenthal et al. 1984); however, their stellar populations are old and evolved (see Renzini 2006 and Conroy 2013 for recent reviews). In addition, analysis of the evolution of the stellar mass and the luminosity functions has demonstrated that there is little evolution in the comoving space density of massive passive galaxies since  $z \sim 1$  (Cimatti et al. 2004; Glazebrook et al. 2004; McCarthy et al. 2004; Daddi et al. 2005; Saracco et al. 2005; Bundy, Treu & Ellis 2007; Pérez-González et al. 2008; Ferreras et al. 2009; Marchesini et al. 2009; Carollo et al. 2013; Muzzin et al. 2013; Lundgren et al. 2014). The prevailing idea is that ETGs formed the bulk of their stars early in the evolution of the Universe (i.e. cluster ETGs at  $z > 3$ , field ETGs at  $z > 1.5$ –2; Thomas et al. 2005; Renzini 2006;

\* E-mail: spini@mpa-garching.mpg.de

Cimatti et al. 2008; Whitaker et al. 2013) and then only at lower redshift (i.e.  $z < 1$ ) may have merged together to build the massive ETGs that we see today in the nearby Universe (Johansson, Naab & Ostriker 2012; Nipoti et al. 2012; Buitrago et al. 2013).

To reconcile these apparently conflicting results and to paint a more robust physical picture for the formation and evolution of these massive systems, enormous effort has been expended in the last two decades to constrain the relative contributions of baryonic, dark matter and black hole constituents of ETGs through stellar dynamical tracers, X-ray studies, and gravitational lensing (e.g. Fabbiano 1989; Mould et al. 1990; Saglia, Bertin & Stiavelli 1992; Franx, van Gorkom & de Zeeuw 1994; Carollo et al. 1995; Arnaboldi et al. 1996; Rix et al. 1997; Loewenstein & White 1999; Gerhard et al. 2001; Romanowsky et al. 2003; Treu & Koopmans 2004; Cappellari et al. 2006; Treu et al. 2006; Thomas et al. 2007; Czoske et al. 2008; Auger et al. 2010a,b; Coccato et al. 2010; Treu 2010; Barnabè et al. 2011; Das et al. 2011; Courteau et al. 2014). A variety of recent observations suggest that baryonic luminous matter, which dominates astrophysical observables, and dark matter, which dominates the dynamics during galaxy formation, are strongly linked. As a consequence, progress in understanding ETGs and more generally the theory of galaxy formation and evolution requires the precise measurement of their stellar and dark matter density profiles, together with measurements of how these quantities depend upon properties such as the mass and the age of the stellar assembly.

Lensing and dynamics observations show that in the inner region of massive ETGs (inside few effective radii,  $R_{\text{eff}}$ ), where baryonic and dark matter are both present, the total mass–density profile is well described by a power-law density profile,  $\rho_{\text{tot}} \propto r^{-\gamma'}$ , with an almost isothermal slope of  $\gamma' \approx 2$  and  $\sim 10$  per cent intrinsic scatter (e.g. Gerhard et al. 2001; Treu & Koopmans 2004; Koopmans et al. 2006, 2009; Barnabè et al. 2009, 2011; Coccato et al. 2009; Auger et al. 2010b; Napolitano et al. 2011; Bolton et al. 2012; Sonnenfeld et al. 2012; Dutton & Treu 2014). However, in the same region, the dark matter density profile seems to be shallower, consistent with a density slope  $1.0 < \gamma_{\text{DM}} < 1.7$ , although this slope is less well-constrained than the total mass–density slope (e.g. Treu & Koopmans 2004; Dye & Warren 2005; Grillo 2012; Sonnenfeld et al. 2012, 2015).

In addition, recent observations as well as theoretical studies based on stellar population and dynamical models (e.g. Bullock et al. 2001; Padmanabhan et al. 2004) indicate that, for a universal initial mass function (IMF), the dark matter fraction ( $f_{\text{DM}}$ ) in the internal region increases monotonically with the mass of the galaxy (e.g. Zaritsky, Gonzalez & Zabludoff 2006; Auger et al. 2010a), a trend that is more conspicuous in the case of slow-rotator ellipticals (Tortora et al. 2009). On the other hand, lensing and dynamics studies also suggest that the luminous stellar mass-to-light ratio ( $\Upsilon_*$ ) scales with the luminous mass of the system (Davis et al. 1985; Bardeen et al. 1986; Bell & de Jong 2001; Girardi et al. 2002; Napolitano et al. 2005; Grillo et al. 2009; Auger et al. 2010b), under the assumption of standard Navarro–Frenk–White dark matter halo profile (NFW; Navarro, Frenk & White 1996).

Despite this progress, it remains difficult to separate the stellar and dark matter components, mostly due to a relatively poor understanding of the precise shape of the stellar IMF and its associated  $\Upsilon_*$ . Uncertainties related to the latter can easily lead to a factor of 2 uncertainty on the inferred stellar mass.

Although it is commonly assumed that the IMF is universal and independent of cosmic time (e.g. Kroupa 2001; Chabrier 2003; Bastian, Covey & Meyer 2010), several authors have suggested that the IMF might evolve (Davé 2008; van Dokkum 2008) or depend

on the stellar mass of the system (e.g. Worthey 1992; Trager et al. 2000; Graves, Faber & Schiavon 2009; Auger et al. 2010a; Graves & Faber 2010; Napolitano, Romanowsky & Tortora 2010; Treu et al. 2010; Cappellari et al. 2012; Martín-Navarro et al. 2015; Posacki et al. 2015). Recent results based on single stellar population (SSP) modelling of galaxy spectra, indicate that the number of low-mass stars ( $M < 0.3 M_{\odot}$ ) increases more rapidly with galaxy mass than the number of high-mass stars (van Dokkum & Conroy 2010, hereafter vDC10; Spiniello et al. 2011, 2012, 2014; Cappellari et al. 2012; Ferreras et al. 2013; La Barbera et al. 2013; Tortora, Romanowsky & Napolitano 2013). This could imply that part of the increase in  $\Upsilon_*$  with galaxy mass can be due to a changing stellar IMF rather than only an increasing dark matter fraction, consistent with the earlier findings by Treu (2010) and Auger et al. (2010b), based on combining lensing, dynamics and stellar population information. The shape of the IMF and the internal fraction of dark matter mass inside massive ETGs cannot be both universal at the same time, but it remains difficult to break the degeneracy between these two effects.

The X-Shooter Lens Survey (XLENs; Spiniello et al. 2011, 2012) aims to take these analyses one step further. With a combined analysis of strong gravitational lensing, dynamical and spectroscopic stellar population studies, the XLENs project will be able to disentangle the stellar and dark matter content of galaxies and, for the first time, directly constrain the normalization, shape, and cut-off mass ( $M_{\text{low}}$ ) of the low-mass end of the IMF and correlate these results with other galaxy properties such as galaxy mass, size, stellar density, and/or stellar velocity dispersion (e.g. Spiniello et al. 2011, 2012, 2014, 2015a; Barnabè et al. 2013).

In particular, our methodology consists of combining spatially-resolved kinematics with high-precision strong-gravitational-lensing measurements of the total mass and the mass–density profile near the lens Einstein radius ( $R_{\text{Ein}}$ ), to obtain a precise internal dark-matter mass fraction inside one effective radius. By taking advantage of the wide wavelength coverage and throughput of the X-Shooter spectrograph, we are able to obtain high-resolution spectra from the UVB to the near-infrared (near-IR) for detailed stellar population and spatially-resolved kinematics studies of the high-mass end of the ETGs up to redshift  $z \sim 0.7$ .

A previously underappreciated result of our approach is that it allows us to tackle the long-standing problem of constraining the low-mass cut-off ( $M_{\text{low}}$ ) for the IMF. In previous studies, the value of  $M_{\text{low}}$  has always been treated as a relatively unconstrained parameter, despite being critical to determine the value of  $\Upsilon_*$ . Stars with masses below  $\sim 0.15 M_{\odot}$  have very little effect on the spectral lines and on the line-index measurements in the optical and near-IR for any assumed IMF slope (Conroy & van Dokkum 2012), but they provide a substantial contribution to the total mass budget of the system for IMF slopes steeper than  $\sim 2$  (Worthey 1994). Therefore, to constrain the value of  $M_{\text{low}}$ , it is necessary to support spectroscopic studies with a combined lensing and dynamics analysis (see Barnabè et al. 2013).

In this paper, we provide an overview of the survey, focusing on the data reduction and analysis process. We present scientific results on the IMF slope and cut-off mass of the full sample in Spiniello et al. (2015a) and other two companion papers of the survey, in preparation. Moreover, we already presented results on the IMF slope of a single very massive lens galaxy used as pilot programme to test our method in the XLENs I (Spiniello et al. 2011). In Section 2, we introduce the XLENs, highlighting its main goals and characteristics and we present its selection criteria. In Section 3, we describe the observations and data reduction process. In Section 4,

we present the spatially-resolved kinematics up to  $\sim 1 R_{\text{eff}}$  obtained from VLT X-Shooter spectra of 10 ETGs with  $\sigma_* \geq 250 \text{ km s}^{-1}$ . We summarize our findings and present our preliminary conclusions in Section 5.

## 2 OVERVIEW OF THE XLENS AND TARGET SELECTION

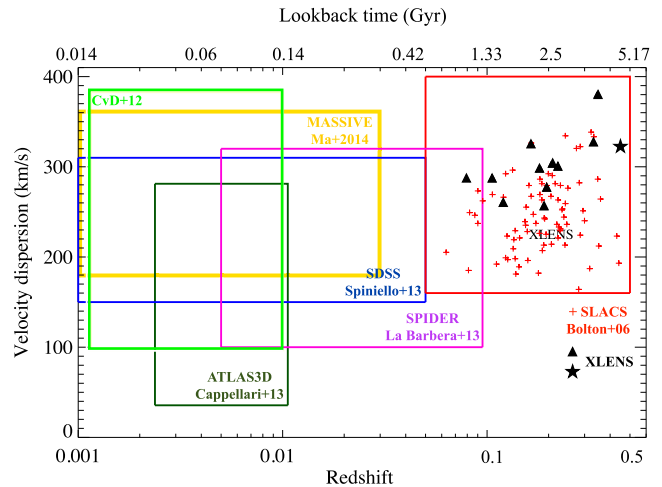
The XLENS aims to study the stellar population of strong early-type lens galaxies, for which exquisite *Hubble Space Telescope* (*HST*) multiband images and very detailed lens models are available. The main goal of the survey is to disentangle the dark matter and stellar mass distributions, as well as to constrain the slope and the cut-off mass of the low-mass end of the stellar IMF directly from spectra, by combining the lensing and dynamical results with the fully independent inferences from spectroscopic stellar population studies.

Our current sample has been selected from the Sloan Lens ACS Survey (SLACS; Bolton et al. 2006, 2008a,b; Koopmans et al. 2006; Treu et al. 2006, 2009; Gavazzi et al. 2007, 2008; Auger et al. 2009, 2010a; Newton et al. 2011). SLACS is a survey of lenses spectroscopically selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000) with follow-up imaging conducted with the Advanced Camera and Spectrograph (ACS) aboard the *HST*. SLACS was initiated in 2003 with the purpose of confirming and imaging galaxies that act as strong gravitational lenses of emission-line background sources. The survey has greatly expanded the number of strong gravitational lens galaxies at redshift  $z \leq 0.5$  with complete redshift information, providing an ideal sample of systems to be analysed with joint lensing and dynamics techniques. In particular, half of the lenses were selected from the SDSS luminous red galaxy (LRG) spectroscopic sample (Eisenstein et al. 2001). The LRG sample is defined by photometric selection cuts that very efficiently select massive ETGs in the redshift range  $0.15 < z \leq 0.5$ , as confirmed by SDSS spectroscopy. These galaxies are very homogeneous in their spectral, photometric, and morphological properties. The remaining targets were selected with the same spectroscopic selection procedure from within the MAIN galaxy sample of SDSS (Strauss et al. 2002). The MAIN sample is more heterogeneous, and therefore a quiescent, absorption-dominated spectral criterion was imposed by requiring the lens candidates to have rest-frame equivalent widths in  $H\alpha$  of  $\text{EW}_{H\alpha} < 1.5 \text{ \AA}$ . The method by which lens candidate were selected is extensively described by Bolton et al. (2006).

The current SLACS sample consists of 131 strong gravitational lens candidates (Bolton et al. 2008a; Auger et al. 2009; Treu et al. 2009; Shu et al. 2015). To date, this represents the largest uniform sample of strong gravitational lenses and it includes 98 ‘grade A’ and 33 ‘grade B’ and ‘grade C’ (likely lenses) confirmed strong galaxy–galaxy lens systems complete with lens and source redshifts,  $F814W$  lens–galaxy photometry, gravitational lens models, and measured stellar velocity dispersions (Auger et al. 2009). Approximately 80 percent of the ‘grade-A’ systems have elliptical morphologies while  $\sim 10$  percent show some spiral structure; the remaining lenses have lenticular morphologies. Such a large and high-quality lens sample provides a unique resource for the quantitative study of massive galaxies.

SLACS is a lensing-selected sample and hence also mass-selected sample, largely peaking around  $1\text{--}2M^*$  galaxies. Shu et al. (2015), published after the XLENS data were acquired, increased the final sample extending it to lenses below  $M^*$ .

From the final SLACS sample of  $\sim 100$  confirmed lenses, the XLENS sample includes only ‘grade-A’ systems with elliptical



**Figure 1.** Parameter space of the XLENS sample (XLENS from SLAC: black triangles, pilot programme: black star) compared with other ETG samples (coloured box). The SLACS systems are plotted as red crosses. Some overlap at the high-mass exists between all these studies but the XLENS galaxies extend the redshift range until a lookback time of 5 Gyr.

morphology that lie above the knee of the luminosity function ( $\sigma_{*,\text{SDSS}} > 250 \text{ km s}^{-1}$ )<sup>1</sup>.

The velocity dispersion cut has been made because of the finding that there is a trend of increasing fraction of ‘non-luminous’ mass beyond  $M^*$  galaxies (Auger et al. 2009, 2010b; Treu et al. 2010; Barnabè et al. 2013). This monotonic increasing of the mass-to-light ratio as a function of the velocity dispersion could be due to an increasing number of low-mass stars (i.e. a low-mass IMF steeper than the Milky Way; Kroupa 2001; Chabrier 2003) or to an increase in internal dark matter, or a combination thereof.

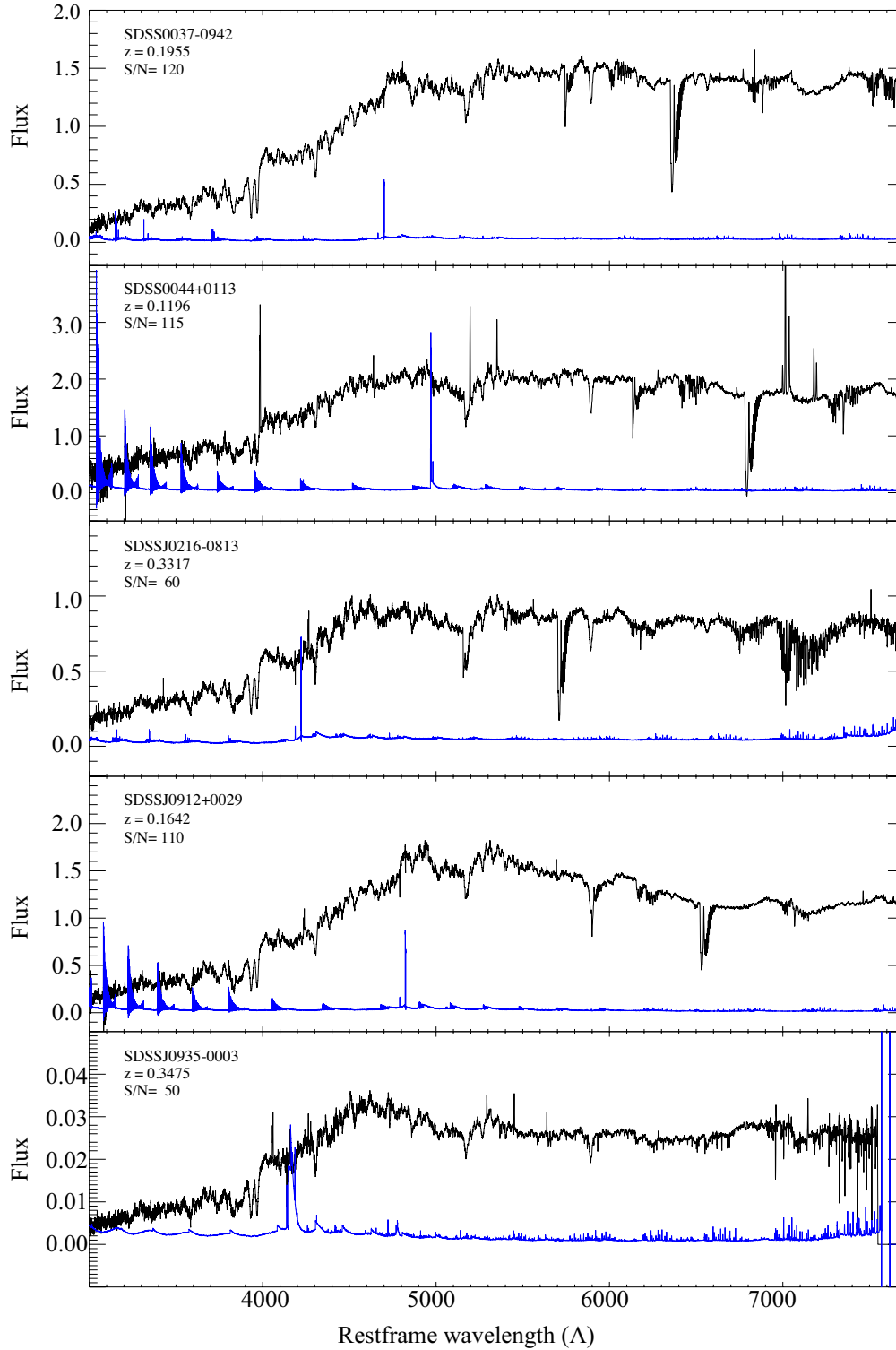
We note that this fraction is very low (less than 10 per cent) around  $M^*$  (Auger et al. 2009, 2010b). Although below  $M^*$ , this fraction might go up again, as suggested by other dynamical and gravitational lensing measurements, such low-mass lenses are rare and much harder to study (see Shu et al. 2015). The current XLENS sample does therefore not include any of these only recently discovered lower mass lens galaxies.

The current XLENS–SLACS sample consists of 11 luminous red galaxies (including one previously published system not selected from SLACS) with apparent  $V$ -magnitudes between 15.8 and 18.1 (from Auger et al. 2009), high-resolution and high signal-to-noise (S/N) *HST* imaging in  $B$ ,  $V$ ,  $I$  and  $H$  bands, and with detailed lensing models constructed by the SLACS collaboration.

In addition to the lens galaxies selected from SLACS, another system has been observed in X-Shooter Guaranteed Time (GTO, P087.A-0620): SDSSJ1148+1930, also known as the ‘Cosmic Horseshoe’ (Belokurov et al. 2007). This lens at redshift  $z = 0.444$  was analysed as a ‘pilot programme’ for the survey. Results on this extremely massive galaxy ( $(\sigma_*)(<R_{\text{eff}}) = 352 \pm 10 \pm 16 \text{ km s}^{-1}$ ) were presented by Spiniello et al. (2011). In the following sections, we limit our discussion to the 10 SLACS-selected XLENS systems (with  $0.11 \leq z \leq 0.44$ ).

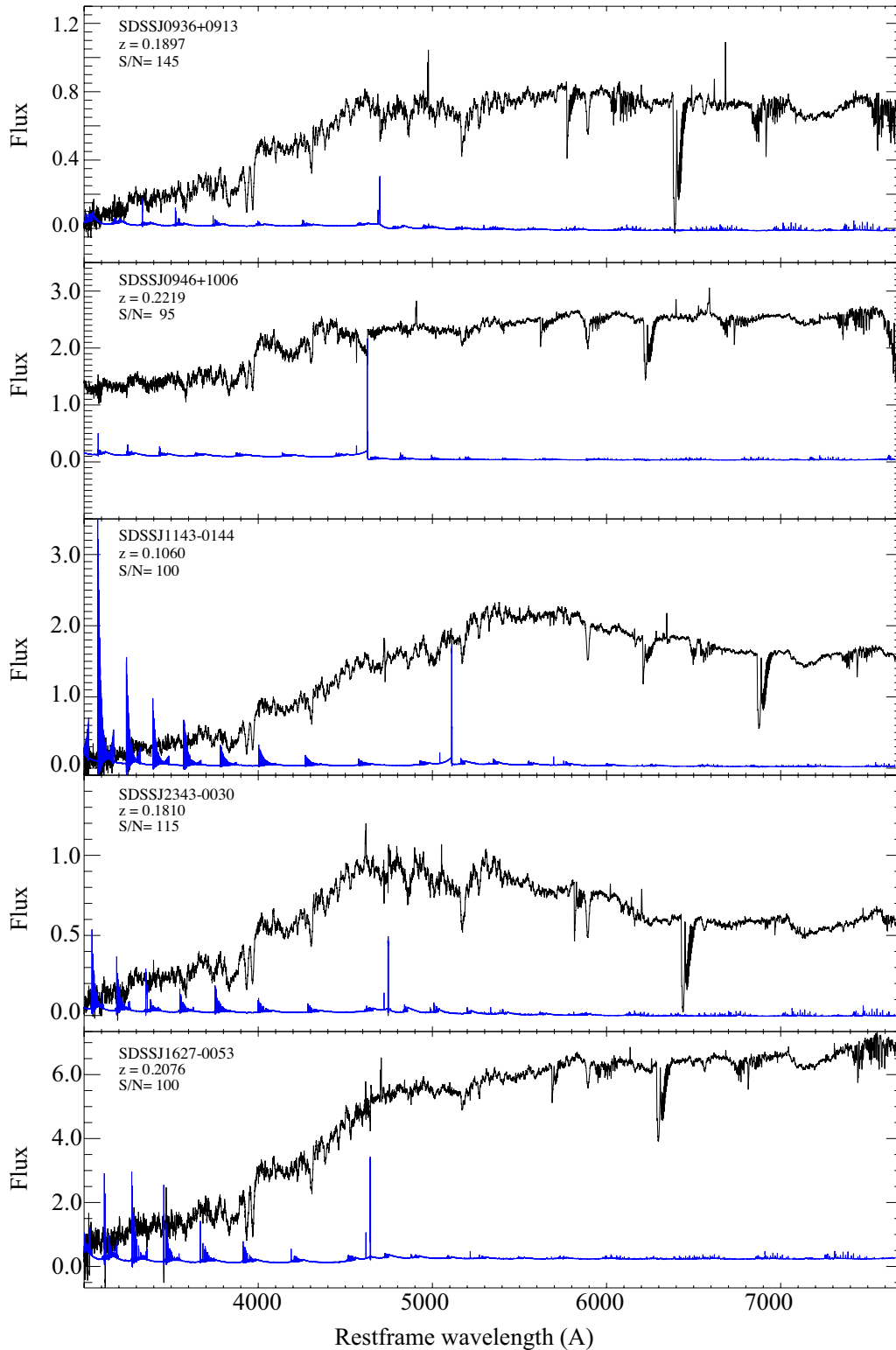
In Fig. 1, the mass–redshift space covered by the final XLENS sample (black triangles and star) is compared to those from the

<sup>1</sup> SLACS is a lensing-selected sample and hence also mass-selected sample, largely peaking around  $1\text{--}2M^*$  galaxies.



**Figure 2.** (a) Final luminosity-weighted UVB–VIS 1D X-Shooter spectra (in black) and respective errors (in blue) extracted from a rectangular aperture of  $\sim 2 \text{ arcsec} \times 1.5 \text{ arcsec}$  centred on the galaxies, shifted to the rest frame and smoothed (3-pixel boxcar) for displaying purposes only. IDs, redshifts of the lens and average S/N (per Å) are shown in the panels. Flux is in units of  $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$ . Telluric absorption lines and emission coming from the background source have not been removed from the spectra. The peak in the error spectra between 4500 and 5500 Å shows the point at which UVB and VIS 1D spectra have been joined.



Figure 2 – (b) *continued*

SLACS parent sample (red crosses) as well as other sample of massive ETGs that have been used to study the low-mass end of the IMF (Conroy & van Dokkum 2012; Cappellari et al. 2013; La Barbera et al. 2013; Ma et al. 2014, coloured boxes). The different

samples overlap in the high-mass regime but XLENs pushes the redshift boundaries beyond the local Universe.

The current sample of lens ETGs with their photometric parameters and physical properties is presented in Table 1.

**Table 1.** Properties of observed systems.

SLACS system	$z_{\text{lens}}$	$z_{\text{BG}}$	$R_{\text{eff}}(\text{kpc})$	$R_{\text{Ein}}(\text{kpc})$	$m_V(\text{mag})^b$	PA slit ( $^\circ$ )
SDSSJ0037–0942	0.1955	0.6322	7.03	4.95	16.90	11.4
SDSSJ0044+0113	0.1196	0.1965	5.56	1.72	16.32	151.3
SDSSJ0216–0813	0.3317	0.5235	12.6	5.53	18.36	81.2
SDSSJ0912+0029	0.1642	0.3239	10.8	4.58	16.56	11.7
SDSSJ0935–0003	0.3475	0.4670	20.7	4.26	17.71	145.2
SDSSJ0936+0913	0.1897	0.5880	6.61	3.45	17.12	145.3
SDSSJ0946+1006	0.2219	0.6085	8.33	4.95	17.78	10.3
SDSSJ1143–0144	0.1060	0.4019	9.21	3.27	15.83	118.7
SDSSJ1627–0053	0.2076	0.5241	6.66	4.18	16.91	6.9
SDSSJ2343–0030	0.1810	0.4630	8.27	4.62	17.17	144.0
SDSSJ1148+1930 <sup>a</sup>	0.4440	2.3815	12.5	29.0	20.02	99.0

Notes. <sup>a</sup>This system is not selected from SLACS but it satisfies the LRG criteria and was observed in a similar set-up during the XLENs pilot programme (Spiniello et al. 2011).

<sup>b</sup>From the *F606 W* filter on WFPC2.

### 3 OBSERVATIONS AND DATA REDUCTION

X-Shooter (Vernet et al. 2011) observations of the all systems were carried out in a total of 30 h of Observation Time (OT), awarded in two periods (P086 and P089).<sup>2</sup> The long-slit mode was used, splitting the beam over three arms: UVB ( $R = 3300$  with a 1.6 arcsec slit); VIS ( $R = 5400$  with a 1.5 arcsec slit); and NIR ( $R = 3300$  with a 1.5 arcsec slit), covering the wavelength range from 3000 to 25 000 Å simultaneously. The 11 arcsec long slit was always centred on the lens galaxy with the position angle (PA) aligned with the major axis of the systems or with an angle that minimizes the contamination from the lensed background source and leaves enough sky region to facilitate accurate sky subtraction. A different number of Observation Blocks (OBs) have been obtained for each system to reach a S/N high enough to perform stellar population analyses (S/N  $\sim 50$  per Å). Each OB had the same layout with three scientific exposures for a total exposure time on target for each arm of  $\sim 2500$  s per OB.<sup>3</sup> During the observations, the seeing varied from  $\sim 0.6$  to  $\sim 0.9$  arcsec. Standard calibration frames and standard stars for flux calibration were obtained after each OB.

The data have been reduced using the ESO X-Shooter pipeline v. 2.0.0 (Goldoni et al. 2006) and the *GASGANO* data file organizer developed by ESO. The pipeline reduction performs standard bias subtraction and flat-fielding of the raw spectra. Cosmic rays are removed using *LACOSMIC* (van Dokkum 2001). For each arm, we extract the orders and rectify them in wavelength space using a wavelength solution previously obtained from the calibration frames. The resulting rectified orders are then shifted and co-added to obtain the final two-dimensional (2D) spectrum. We extract a one-dimensional spectrum (1D) from the resulting 2D merged spectrum, using our own IDL code that also produces the corresponding error file and bad pixel map. The final S/N in the UVB+VIS spectrum varies from system to system, with a minimum of  $\sim 50$  and a maximum of  $\sim 145$  per Angstrom ( $0.2 \text{ Å pixel}^{-1}$ ). We finally perform an iterative sigma clipping to clean the spectrum of any residual bad pixels, sky lines and cosmic rays. No telluric correction has been applied so that prominent atmospheric absorption bands can still be seen

in the final UVB+VIS spectra shown in rest-frame wavelengths in Figs 2(a) and (b). For some of the systems, it is also possible to see emission lines from the background source, although the chosen PA minimizes their contribution to the stellar spectra. We mask these lines as well as telluric absorption when extracting the spatially-resolved kinematic profile.

Because the near-IR spectrum still suffers seriously from sky-line residuals that are difficult to remove using the current pipeline, we limit ourselves in this paper to the UVB–VIS region of the spectrum and defer a full analysis of the infrared data to future publications.

### 4 STELLAR KINEMATICS

#### 4.1 Global kinematics

We measure the luminosity-weighted line-of-sight velocity dispersion (LOSVD) of the lens galaxies from the final 1D UVB–VIS spectra extracted from a rectangular aperture of  $2 \text{ arcsec} \times 1.5 \text{ arcsec}$  centred on the galaxy. We use the Penalized Pixel Fitting (PPXF) code of Cappellari & Emsellem (2004) to determine the combination of stellar templates which, when convolved with an appropriate LOSVD, best reproduces the galaxy spectrum. The best-fitting parameters of the LOSVD are determined by minimizing a  $\chi^2$  penalty function, yielding the mean velocity and velocity dispersion ( $v$  and  $\sigma_*$ , respectively) and their uncertainties. In Fig. 3, we show examples of PPXF fits for the highest and lowest S/N systems.

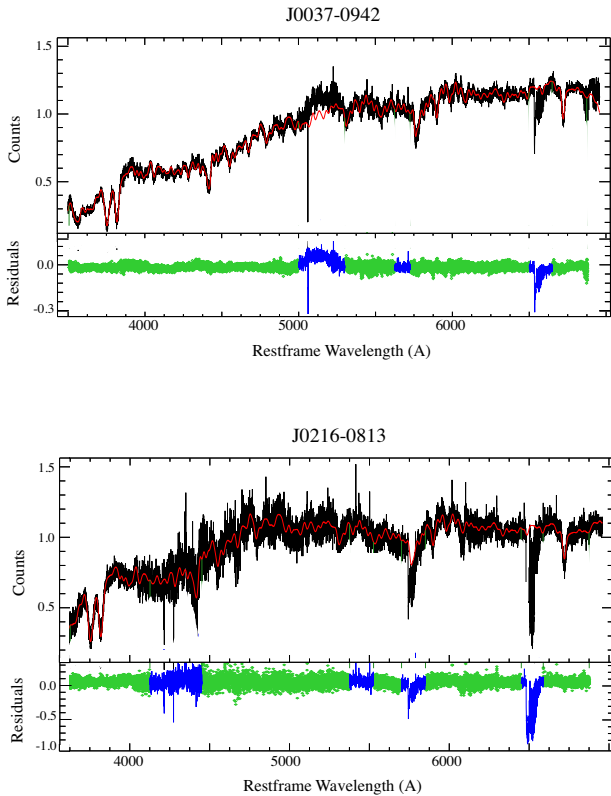
We focus on the absorption lines between 3500 and 6500 Å (including Ca H&K, G4300,  $H_\beta$ ,  $Mgb$ , strong Fe lines, NaD and some TiO molecular absorption bands). To minimize errors due to potential mismatches between the resolution of the templates and the galaxy spectrum, we use X-Shooter spectra obtained as part of the X-Shooter Stellar Library (XSL) survey<sup>4</sup> (Chen et al. 2014), with higher instrumental resolution. For the galaxy spectrum, we use a 1.5-arcsec slit (corresponding to  $\langle \sigma_{\text{instr}} \rangle \sim 35 \text{ km s}^{-1}$ , in the observed frame, and to  $\langle \sigma_{\text{instr}} \rangle \sim 28 \text{ km s}^{-1}$  in the rest frame) while for the stellar templates, the slit width are 0.5 and 0.7 arcsec in UVB and VIS, respectively, corresponding to  $\langle \sigma_{\text{instr}} \rangle \sim 12 \text{ km s}^{-1}$ . As a test of the accuracy of our measurements, we use the more heterogeneous MILES<sup>5</sup> stellar template library by Sánchez-Blázquez et al. (2006). We select 100 stars (F, G, K, M) in the range 3525–7500 Å,

<sup>2</sup> 15 h OT during P86 (P086.A-0312, PI: Koopmans) and 15 h OT during P89 (P089.A-0364, PI: Spiniello).

<sup>3</sup> In the NIR arm, the total exposure time is the product of DIT (Detector Integration Time), NDIT (Number of DITs) and NINT (Number of Integrations):  $T = \text{DIT} \times \text{NDIT} \times \text{NINT}$ . We used for each of the three scientific exposures 3 DITs of 278 s.

<sup>4</sup> <http://xsl.u-strasbg.fr>

<sup>5</sup> <http://www.iac.es/proyecto/miles/pages/stellar-libraries/miles-library.php>



**Figure 3.** Two examples of PPXF fits. The upper row shows one of the best cases ( $\chi^2/\text{DOF} \sim 1.15$ ), while the lower row shows the worst case ( $\chi^2/\text{DOF} \sim 1.65$ ). Top panels: UVB+VIS galaxy spectrum (black) and correspondent best-fitting template (red), both in rest-frame wavelength. Bottom panels: residuals from the fit. Bad pixels excluded from the fitting procedure (sky line, telluric lines) are shown in blue. See the text for more information.

with  $2.5 \text{ \AA}$  FWHM spectral resolution (corresponding roughly to  $30 \leq \sigma_{\text{MILES}} \leq 70 \text{ km s}^{-1}$  in the selected wavelength range), which is comparable to the XLENs spectra resolution in the selected regions ( $\sigma_{\text{XSH}} \sim 35 \text{ km s}^{-1}$ ) that have been smoothed to the same spectral resolutions with a Gaussian. Fitting with different stellar templates does not appreciably affect the resulting LOSVD. As a second

test, we fit the same stellar templates to two different spectral regions for each galaxy separately (blue region:  $3800\text{--}5000 \text{ \AA}$  and red region:  $5000\text{--}6500 \text{ \AA}$ ). Only for two systems (SDSSJ0936+0913 and SDSSJ1143-0144) do we find slightly different results between the blue and the red parts of the spectrum, but the results are always consistent within  $2\sigma$ . The scatter between the different fits is used to estimate additional systematic uncertainties related to template mismatch and spectral coverage. These errors are folded into the final error budget. We report our results and the comparison with other published velocity dispersion results for each ETG in Table 2. We find good agreement between our values extracted from a rectangular aperture of  $2 \text{ arcsec} \times 1.5 \text{ arcsec}$  and the SDSS velocity-dispersion measurements obtained in the  $3 \text{ arcsec}$ -diameter spectroscopic fibre (for most of the systems within  $1\sigma$  error). We also find good agreement with the results by Czoske et al. (2012) obtained from (a larger) aperture-integrated spectra from the VIMOS Integral-Field data on five systems that overlap with the XLENs sample.

#### 4.2 Spatially-resolved kinematics

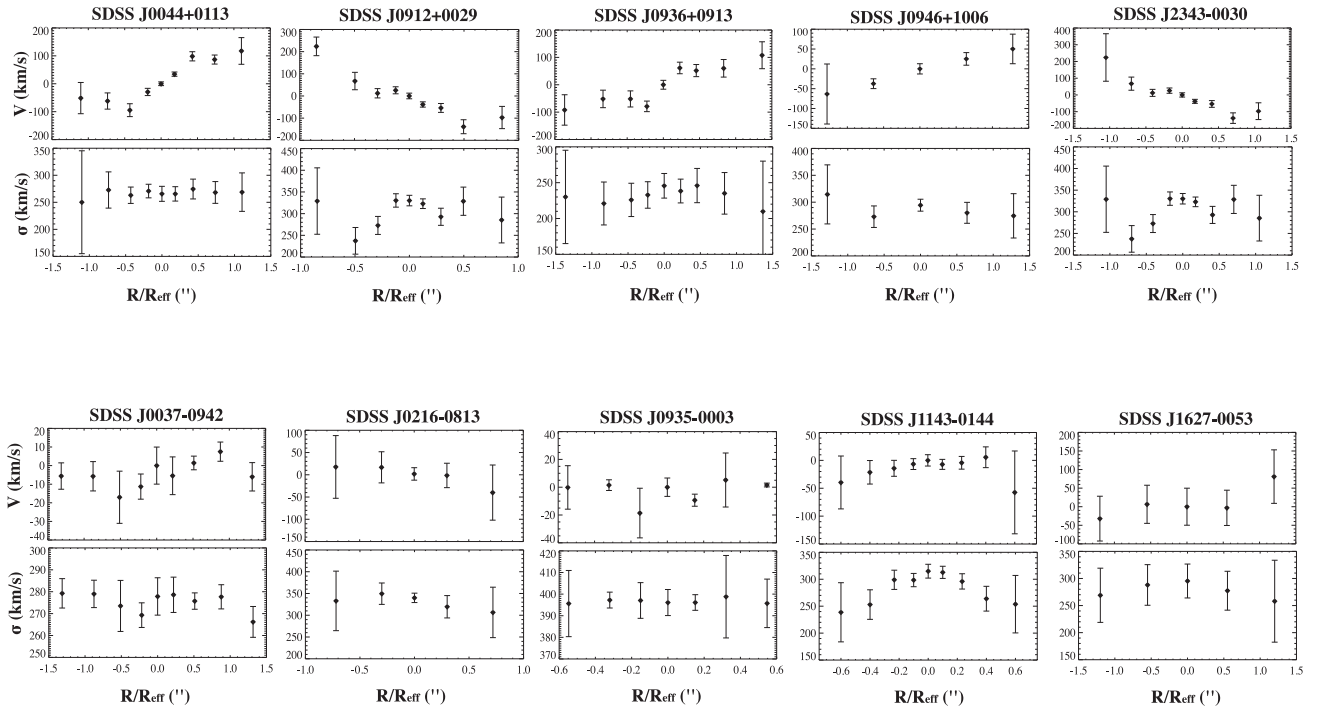
To extract the spatially-resolved kinematic information, we define a number of spatially-varying apertures (with adequate S/N ratio,  $S/N > 10$ ) along the radial direction for each galaxy, and we sum the signal within each aperture. Apertures are always defined to be larger than the seeing in order to have approximately independent kinematic measurements for each aperture. The streaming motion and velocity dispersion are measured from each spatially-resolved spectrum using PPXF as described above. Also in this case we perform tests to check our error determinations: we fit the blue and red spectral regions separately, masking out the most prominent telluric lines in the VIS-red range; and we use different stellar templates from the two different stellar libraries (11 XSL stars of G, K and M spectral types and a sub-selection of MILES stars of the same spectral types). The uncertainties on the inferred kinematics are estimated by adding in quadrature the formal uncertainty given by PPXF and the scatter in the results for different templates and spectral regions.

Our goal is to determine the kinematic profiles up to about one effective radius for all the systems. The first and second moments of the LOSVD out to their effective radii, complemented with two-integral axisymmetric models (Barnabè & Koopmans 2007; Barnabè et al. 2009) allow us to obtain a precise measurement of

**Table 2.** Luminosity-weighted stellar kinematics of the lenses.  $\langle\sigma_{\text{XSH}}\rangle$  has been extracted from a rectangular aperture of  $2 \text{ arcsec} \times 1.5 \text{ arcsec}$  centred on the galaxies, while  $\sigma_{\text{SDSS}}$  is measured within an aperture with a diameter of  $3 \text{ arcsec}$ . VIMOS velocity dispersions were measured from aperture-integrated spectra from data from the VIMOS Integral-Field Unit (Czoske et al. 2012).

ID name	$\langle\sigma_{\text{XSH}}\rangle \text{ (km s}^{-1}\text{)}$	$\sigma_{\text{SDSS}} \text{ (km s}^{-1}\text{)}$	$\sigma_{\text{VIMOS}} \text{ (km s}^{-1}\text{)}$
SDSSJ0037–0942	$277 \pm 6$	$279 \pm 14$	$245.3^{+6.9}_{-7.2}$
SDSSJ0044+0113	$260 \pm 8$	$266 \pm 13$	–
SDSSJ0216–0813	$327 \pm 19$	$333 \pm 23$	$340.7^{+7.8}_{-7.7}$
SDSSJ0912+0029	$325 \pm 10$	$326 \pm 16$	$306.5^{+10.9}_{-11.4}$
SDSSJ0935–0003	$380 \pm 22$	$396 \pm 35$	$330.4^{+9.0}_{-8.5}$
SDSSJ0936+0913	$256 \pm 18$	$243 \pm 12$	–
SDSSJ0946+1006	$300 \pm 22$	$263 \pm 21$	–
SDSSJ1143–0144	$287 \pm 18$	$269 \pm 10$	–
SDSSJ1627–0053	$303 \pm 23$	$290 \pm 20$	$272.6^{+7.8}_{-8.9}$
SDSSJ2343–0030	$298 \pm 21$	$269 \pm 16$	–





**Figure 4.** Spatially-resolved kinematics of the lenses. Upper panels show the systems which have mild rotation and are classified as fast rotators from Fig. 5, lower panels show systems which do not rotate and are classified as slow rotators.

the logarithmic slope of the total mass–density profile of the lens galaxy (e.g. Czoske et al. 2008; Barnabè et al. 2011, 2013; Spiniello et al. 2011).

The rotation and the velocity dispersion profiles for the 10 XLENs–SLACS galaxies are shown in Fig. 4. The upper line shows systems with moderate rotation, whereas the lower line shows systems with almost-flat velocity profiles. The weighted average values are always consistent within the formal error with the luminosity-weighted values for an aperture of  $2 \text{ arcsec} \times 1.5 \text{ arcsec}$ .

We infer the averaged angular momentum ( $\lambda_R$ ) using the definition of Emsellem et al. (2011), with the spatially-resolved rotation velocity and velocity dispersion. We derive the radial  $\lambda_R$  profiles (left-hand panel of Fig. 5) and plot them as a function of ellipticity ( $\epsilon$ ), calculated from the lensing models ( $\epsilon = 1 - q^*$ , where  $q^*$  is the axis ratio). This allows us to split the galaxy sample into slow and fast rotators. The  $\lambda_R$  parameter quantifies the (apparent) global dynamical state of a galaxy and has been used by the ATLAS<sup>3D</sup> team (Cappellari et al. 2011) to show that fast and slow rotators are physically distinct classes of galaxies with different orbital distribution and mass assembly histories. Simulations have demonstrated that galaxy mergers (major and minor) have a significant influence on the rotation properties: major mergers produce a significant increase in the angular momentum of the dark matter haloes at large distances from the centre (Vitvitska et al. 2002) but it leads to a redistribution of the angular momentum of the central stellar component outwards (e.g. Bournaud, Combes & Jog 2004). Fast rotators have either preserved or regained their specific angular momentum in the central part and therefore they cannot have experienced major dry mergers which would expel most of the angular momentum outwards and avoid the building of a rotation-dominated disc-like structure (Emsellem et al. 2007; Naab et al. 2014). Concluding, the  $\lambda_R$ , interpreted as a proxy of the specific angular momentum, is an

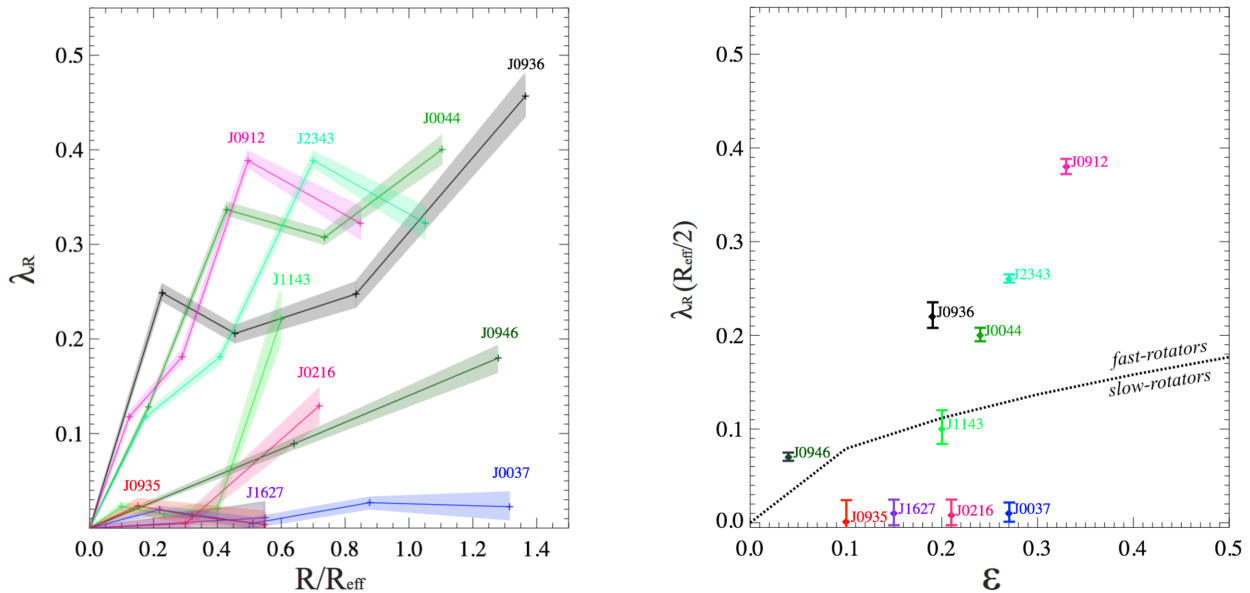
important quantity that allows one to link present-day kinematical profiles to the cosmological formation history of a galaxy.

The right-hand panel of Fig. 5 clearly shows that five of our galaxies are classified as slow rotators, whereas the other five are classified as fast rotators, but none of them show a very high  $\lambda_R$  value. It also appears that the most massive galaxies in our sample tend to rotate more slowly than the least massive ones (with the exception of J0912, which is classified as fast rotator even though it has  $\sigma > 300 \text{ km s}^{-1}$ ). This result confirms the ATLAS<sup>3D</sup> result that slow rotators dominate the high-mass end of ETGs.

## 5 SUMMARY AND CONCLUSIONS

In this paper, we have presented our spectroscopic follow-up survey of massive early-type lens galaxies: XLENs. In particular, we

- (i) highlight the scientific motivations and main goals of XLENs;
- (ii) present the current sample of 11 massive early-type lens galaxies, discussed the selection criteria and described the data reduction process for the XLENs–SLACS galaxies. The remaining lens, also known as ‘The Cosmic Horseshoe’, has been used as a pilot programme of the survey and is the subject of the first paper of the series (XLENs I; Spiniello et al. 2011);
- (iii) present the spatially-resolved kinematic profiles up to  $\simeq 0.8\text{--}1.5 R_{\text{eff}}$  for the lens galaxies. We found luminosity-weighted velocity dispersions mostly within  $1\sigma$  agreement of those calculated from SDSS. Our velocity dispersions also agree with the results of Czoske et al. (2012) extracted from VIMOS integral-field spectra on five systems in common;
- (iv) derive the  $\lambda_R$  spatial profiles and calculate  $\lambda_{R_{\text{eff}/2}}$  to split the sample into fast and slow rotators. We confirmed the ATLAS<sup>3D</sup> results



**Figure 5.** Left: radial  $\lambda_R$  profiles. The  $1\sigma$  contours are showed with coloured shaded regions. Right: the  $\lambda_{R_{\text{eff}}/2}-\epsilon$  relation for the XLENs galaxies. The dotted black line shows the division between slow (below the line) and fast (above the line) rotators within  $R_{\text{eff}}/2$ . All most massive galaxies in our sample, except for J0912, belong to the slow-rotator group.

that slow rotators dominate the high-mass end of the galaxy mass function.

The combination of high-S/N spectroscopy from X-Shooter with a strong gravitational-lensing mass determination enables us to conduct an in-depth study of the dark and luminous matter within  $\sim 1 R_{\text{eff}}$  and for the first time constrain the normalization, shape and cut-off mass ( $M_{\text{low}}$ ) of the low-mass end of the IMF. We make use of the state-of-the-art joint lensing and kinematic code (Barnabè et al. 2012) and new SSP models (Conroy & van Dokkum 2012) that have been constructed specifically for the purpose of measuring the IMF slope down to  $\sim 0.1 M_{\odot}$  for old, metal-rich stellar populations. The version of the SSP models that we use have been extended beyond their original parameter spaces, to explore supersolar  $[\alpha/\text{Fe}]$  and supersolar metallicity and to disentangle elemental enhancements, metallicity changes and IMF variations in massive ETGs with star formation histories different from the solar neighbourhood (following the method presented in Spiniello, Trager & Koopmans 2015b).

In two following papers of the series, we use the joint lensing and dynamics code CAULDRON<sup>6</sup> to perform the analysis of the total mass distributions for the XLENs systems. We put constraints on the internal dark matter fractions, the orbital structure, the shape and flattening of the dark matter halo and investigate possible correlations of these quantities with physical parameters of the lens systems such as size, stellar density and stellar velocity dispersion. Thanks to the high quality of our lensing and kinematics data, this technique also makes it possible to put firm constraints on the stellar mass of the analysed galaxies independently of assumptions about their stellar IMF or knowledge of their stellar populations.

Moreover, we apply to the sample the line-index-based stellar population analysis presented in Spiniello et al. (2014) to study in detail the stellar contents of the systems and to constrain their

integrated ages, metal abundances and IMF slopes and to search for possible correlations between stellar population parameters and structural properties of the systems (i.e. mass, size, stellar density, and/or velocity dispersion).

Finally, in a letter already submitted, we study the impact of a non-universal IMF slope and/or a non-universal IMF low-mass cut-off on the inferred mass-to-light ratios by comparing the two completely independent constraints on the stellar mass, one from the fully self-consistent joint lensing+dynamics (L&D) analysis, and the other from spectroscopy and SSP modelling. For this study, we follow the approach presented in Barnabè et al. (2013) to obtain the joint 2D posterior PDF in the slope- $M_{\text{low}}$  space.

In the future, we plan to extend the current sample, observing lenses within the same range of velocity dispersions ( $\sigma_{*,\text{SDSS}} > 250 \text{ km s}^{-1}$ ) at higher redshift (up to  $z \sim 1$ ) to test possible evolution of the IMF with cosmic time. We also plan to observe low-mass ETGs to build a complementary data set to our more massive ETGs with the purpose of covering a wider stellar mass range and to test possible variation of the IMF slope with structural and stellar parameters, other than the stellar mass of the galaxy (e.g. total dynamical density, as we recently suggested in Spiniello et al. 2015a).

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<sup>6</sup> ‘Combined Algorithm for Unified Lensing and Dynamics Reconstruction’ (Barnabè & Koopmans 2007; Barnabè et al. 2009, 2012)

Hemisphere, Chile (P086.A-0312, PI: Koopmans, and P089.A-0364, PI: Spiniello).

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